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Exergy Analysis of A Hermatic Turbine 500 kW Organic Rankine Cycle Geothermal Binary Power Plant

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Abstract – Up to 2025, Indonesia will approximately utilize 150 MWe promising small scale of waste heat geothermal sources for electricity power plants. As the characteristic of the brine water is has a low grade of heat and low grade of enthalpy. Therefore, the Organic Rankine Cycle geothermal binary power plant system is well suited to maximize these potentials to construct low-capacity power plants to maximize the utility of geothermal power plant. The aim of this research is to examine a case study on the performance of the turbine of the 500 kW ORC power plant. The turbine is rotated by the working fluid. The working fluid used for this research is n-pentane. An exergy analysis is performed to reduce losses or energy wasted, especially on the turbine component. Results of analysis with random data collected in April to July 2018 from the turbine system. The result shows that the minimum efficiency of 56.24% is when inlet heat source temperature of 117^{o}C and ambient temperature of 22^{o}C. While the maximum efficiency of 69.92% at an inlet heat source temperature of 133^{o}C and ambient temperature of 33oC. The largest exergy losses is recorded at 175.83 kW, while the smallest exergy losses is recorded at 130.78 kW and average exergy losses is at 154.86 kW.

Keywords: Organic Rankine Cycle, Turbine, Exergy, Efficiency, Losses.

1. Introduction

Electrical energy is the most important energy in the development of a country. This can be seen from the large amount of electricity consumed every year. In Indonesia, a significant increase in the number of people making more electrical energy needed by many people, this causes energy fuels dwindling been inevitable. In a previous research, the authors identify some things that need to be determined to complete the cycle. The different place also affected the optimization of the design, it is necessary to re-analysis of turbine components exergy in the ORC cycle

By utilizing geothermal potential with a low temperature for a capacity of 500 kW power generation using Organic Rankine Cycle technology, the research question for this research is how to find out the output of the Turbine Organic Rankine Cycle geothermal power plant work, and how to determine the exergy efficiency in Turbines in the Organic Rankine Cycle geothermal power plant system. The boundary problem used in this research is focused on Turbine Exergy analysis on Organic Rankine Cycle (ORC) system with a capacity of 500 kW and Exergy Efficiency in Organic Rankine Cycle (ORC) system turbines.

The purpose of this research is to analyze the exergy in the turbine with a manual calculation, namely obtain Turbine Energy Performance and Balance on Organic Rankine Cycle (ORC) capacity of 500 kW and obtain the amount of Energy availability in the Turbine and the Efficiency of Turbine Exergy in Organic Rankine Cycle (ORC) capacity of 500 kW.

2. Literature Review

Santoso et al., (2011) explains that the energy source for large capacity gas / steam power generation systems is dominated by fossil fuels which are currently depleting and the application is always creating greenhouse gas emissions. The consequences, the engineering and operation of a good power generation system is very important so that energy consumption and greenhouse gas emissions can be reduced. Exergy analysis is an interesting tool to meet this need because it can identify irreversibility locations or exergy losses and the level of inefficiency of the power generation system. Thus, the exergy analysis provides the information needed to improve the power generation system systematically and efficiently. A case research of this research, this method is implemented in combined-cycle gas-steam power plant in Combined Cycle Power Plant Unit Inderalaya, South Sumatra. The research results show that components that provide the greatest contribution to the destruction of eksergi is combustor. The percentage of exergy extermination ratio in each component to the maximum total exergy destruction was obtained in the combustion chamber (59.76%), followed by HRSG (13.19%), gas turbine (9.74%), compressor (7.39%), steam turbine (7.06%), condenser (2.71%) and then pump (0.15%). The exergy carried by the exhaust gas into the atmosphere (4.0% of total fuel exergy) is considered a loss. While the overall exergetic efficiency of the gas-steam turbine combination cycle is relatively low (38.4%).

Ayu., (2012) explained about research using EES software that by increasing the turbine inlet temperature, the net power of the turbine will also increase due to the high efficiency of the turbine, where about 80% of the exergy value in the turbine is maximally converted to mechanical energy to turn the turbine and generate electrical energy. Likewise with the increase in the exergy efficiency of the ORC cycle as a whole, which is followed by an increase in energy efficiency. Because efficiency is closely related to changes in net power output from the cycle. (Li et al., 2012) in mention the thermal efficiency of ORC at different heat source temperatures around 100, 90, 80, and 70oC was explored. The irreversibility thermodynamics that occur in the evaporator, condenser, turbine, pump, and separator are revealed. ORC feasibility for low temperature applications indicated by the hot side temperature of about 80 ° C, the thermal efficiency of 7.4% and 0.68% turbine isentropic efficiency can be achieved. It further showed that exergy destruction caused by heat transfer through a fairly large temperature difference at the evaporator is the largest in the energy conversion process, followed by a condenser. Exergy destroyed in heat exchange amounted to 74% of the total losses exergy. Efficiency of exergy total system is approximately 40%, thus a way to improve the efficiency of exergy required. HCFC-123, dry fluid, is experimentally confirmed to be very hot after the expansion in this research. Regenerator HCFC-123 to be heated before it enters the evaporator. While the heat-transfer configuration with two oil cycles can be a good solution to overcome thermodynamic losses from one-stage evaporator.

2.1. Thermodynamic System

Thermodynamics is defined as the basic science of energy. Thermodynamics comes from Greek therme which means heat and dynamis which means power, descriptively defined as an attempt to turn heat into energi (Cengel and Boles., 2002a).

2.1.1. First Law of Thermodynamics

First Law of Thermodynamics is one of the most fundamental natural principle is the principle of conservation of energy (energy conservation principle). The rule states that energy can change from one form to another, but the total amount of energy remains the same. Mathematically stated that the amount of energy of a system is equal to the difference between incoming and outgoing energy.

$\Delta E = Ein – Eout$
(1)

Equation (1) is known as the energy balance equation. The first law of thermodynamics also states that energy is a thermodynamic property (Cengel and Boles., 2002b).

2.1.2. Second Law of Thermodynamics

The Second Law of Thermodynamics also states that Energy and objects can be converted to other forms by consuming the quality of energy / objects. Quality can be improved; however, this can only be done at a large cost in the form of greater quality degradation elsewhere. According to the second law of thermodynamics, energy is constantly decreasing quality of each energy used in the process. "The quality of energy" called EXERGY.

$Ex\ H = \dot{Q} – T_0\ \Delta S$
(2)
$\dot{Q} = \dot{m}\ (h_1 – h_0) – W$
(3)
Whereas:

- $\dot{Q}$ = Heat Flow Rate
- T_0 = Ambient temperature
- ΔS = Total Entropy
- h_1 = Enthalpy state entry
- h_0 = Enthalpy at ambient temperature

The form of general equation in equation (2), exergy or also called available energy (available energy) at temperature H and environmental temperature T0.

2.1.3. Enthalpy

Enthalpy (H) is the amount of energy the system has at a constant pressure. Enthalpy is defined as the amount of energy contained in the system (E) and work (W).

$H = E + W$
(4)

The law of conservation of energy explains that energy cannot be created and cannot be destroyed, but can only be changed from one form of energy to another. The energy value of a material cannot be measured, only energy changes can be measured (ΔE). Similarly, enthalpy, enthalpy cannot be measured, it can only be measured enthalpy change (ΔH). At constant pressure, enthalpy changes can be measured;

$\Delta H = \Delta E + P.\Delta V$
(5)
$\Delta E = q + W$
(6)
$W_{system} = -PV$
(7)

Subtitution equation (6) and (7) into:

$\Delta H = (q + W) P\Delta V$
(8)
$\Delta H = (q - P.\Delta V) + P.\Delta V$
(9)
$\Delta H = q$
(10)

So, at a constant pressure enthalpy change (ΔH) is equal to the heat (q) absorbed or released (Brady., 1990).

2.1.4. Entropy

The theory of entropy (S) made by Rudolf Clausius, which refers to the thermodynamic properties. If the calculated total energy can't be used in some processes such as thermodynamics, the entropy concept can be used. The tendency of the system or the reaction to proceed in a certain direction is called the entropy of the system. In other words, entropy is the degree of disorder or chaos in a system. The International Unit for entropy is Joule per Kelvin (J / K), the principal of this unit is the energy divided by temperature. Entropy and entropy change can be written in equation:

$\Delta S = Q/T$
(11)
Whereas:
Q = Heat Absorption
T = Temperature

2.2 ORG Generation System

The ORC generator system has 4 main components, namely evaporator, turbine, condenser and pump. The evaporator is used to evaporate the organic fluid from the liquid phase to hot steam before it is inserted into the turbine. The turbine is used to expand and degrade organic fluid pressure. The turbine is connected to a generator that will produce electricity. After passing through the turbine, the working fluid will be liquefied in a condenser which would then be pumped into the evaporator.

2.2.1 Pump

In the Rankine Cycle, the pump is responsible for raising the pressure of the fluid (refrigerant) before entering the evaporator. The higher the fluid pressure, the higher the heat energy that can be absorbed by each unit of fluid mass.

2.2.2 Evaporator

Evaporator is a device that has a function to convert the whole or part of a solvent from a solution in the form of a liquid to vapor so that only leaves a solution that is more dense or thick, the process that occurs in the evaporator is called evaporation. In the industrial world, the benefits of this tool are for initial thickening of the liquid before further processing, reduction of liquid volume and to reduce water activity. Evaporator has two basic principles, to exchange heat and to separate the water vapor dissolved in the liquid. In general, the evaporator consists of three parts, namely: Heat exchanger, The evaporation part (the place where the liquid is boiling then evaporates) , and The separator for separating vapor from the liquid. The results of the evaporator are solids or concentrated solutions and evaporated solutions usually consist of several volatile components (volatile).

2.2.3 Hermatic Turbine

Hermatic Turbine is a rotating machine that takes energy from fluid flow. Simple turbines have one moving part, "rotorblade assembly". The moving fluid makes the propeller spin and produce energy to drive the rotor. Steam Turbine Includes Machines Energy conversion that converts the potential steam energy into kinetic energy at the nozzle and is then converted into mechanical energy in turbine blades mounted on the turbine shaft. The mechanical energy produced in the form of rotation of the turbine shaft may directly or with the help of reduction gears connected to the driven mechanism. To generate electricity, the mechanism is a shaft-driven generator. When compared with driving with electric power such as diesel, turbines have advantages such as better use of heat, easier round control, does not produce an electric spark, not affected by the hot surroundings, and used steam can be reused (for drying process, etc.).

In the Organic Rankine Cycle system, Turbine work can be known by the generator equation divided by the efficiency of the generator to the turbine. The efficiency of the turbine generator can be assumed to be equal to 98% refers design of turbine generator.

2.2.4 Condenser

A condenser is a device consisting of a pipe network and is used to convert steam into a liquid (water). It can also be interpreted as a heat exchanger (heat) which functions to condense the fluid. In its use the condenser is placed outside the room being cooled so that the heat that comes out during operation can be discharged so that it does not interfere with the cooling proces**or**

2.4. Exergy Concept

Exergy is energy that can be used (energy available) or a measure of the availability of energy to do work. The exergy of a resource provides an indication of how much work the resource can do in a given environment. Exergy can be transferred between systems and can be destroyed by irreversibility in the system. The concept of exergy explicitly shows the use (quality) of an energy and substance as an addition to what is consumed in the conversion or energy transfer stages. One of the main uses in the concept of exergy is the exergy balance in thermal system analysis. Identification and qualification of this loss allows for evaluation and improvement of thermal system design. Exergy analysis method can show the quality and quantity of heat loss and location of energy degradation (measuring and identifying the causes of energy degradation). Most cases of thermodynamic imperfections can be detected by exergy analysis. Actual work and reversible work equations are often formulated in the equation of the exergy function for an open system and a closed system. Until now it was considered important to determine the potential work of a system in certain circumstances towards equilibrium with the environment while a number of heat transferred was the only interaction with the environment.

2.4.1 Dead State

When the system and the environment is at equilibrium or any work or changes in temperature (T) and pressure (P) suddenly, then the condition is called as the state or the phase equilibrium state dead. Recommended for dead state / die position is at standard atmospheric 298.15 K and 1.01325 bar (1 atm) Ui (2012). Dead state is also better if the velocity of the fluid is a closed system is zero and the potential gravitational energy is also zero.

2.4.2 The Transfer of Heat Exergy

Exergy can be calculated as follow:

$\dot{E}x = \dot{Q}\ (1 - T_0/T)$

(12)

Whereas:

T_0 = Ambient Temperature

T = Heat Source Temperature

$\dot{Q}$ = Heat Transfer

2.4.3 Thermomechanical Exergy

Thermomechanichal exergy can be calculated as follow:

$ex = h_1 - h_0 - T_0\ (s_1 - s_0)$

(13)

Whereas:

h_1 = Initial Enthalpy

h_0 = Ambient Enthalpy

s_1 = Initial Enthalpy

s_0 = Ambient Enthalpy

2.4.4 Exergy Losses

Exergy can be annihilated. Exergy irreversibility or losses can be calculated as follow:

$\dot{E}D = \dot{W}_{rev,out} - \dot{W}_{out}$

(14)

Whereas:

$\dot{W}_{out}$ is actual duty in the ORC turbine.

$\dot{W}_{rev,out}$ is reversible duty in the ORC turbine.

Reversibel can be calculated as follow:

$\dot{W}_{rev,out} = \dot{m}[(h_1\text{-}h_2) – T_0(s_1\text{-}s_2) - \Delta ke - \Delta pe]$

(15)

In a steady condition, we can disregard the total of kinetic and potential energy.

2.4.5 Exergy Efficiency

Efficiency can be defined as follow:

$$\eta_{ex} = (\dot{E}_{ou}t/\dot{E}_{in}) \times 100\% \quad (16)$$

$$\eta_{ex(turbine)} = (\dot{W}_{out}/(\dot{W}_{rev,out})) \times 100\% \quad (17)$$

2.4.6 Closed Loop Exergy

A closed loop exergy system can be defined as a maximum duty output which obtains from a combination of system-atmosphere.

2.5 Working Fluid Selection

Working fluid can be regarded as a fluid which produce mechanical energy. In an ORC power plant, working fluid (refrigerant) is being used to rotate the turbine. Refrigerant is selected because it has a considerably low boiling point. There are rather wide range selections of refrigerant. It depends on the needed specification. There are several requirements to select fluid for an ORC:

1. The evaporation pressure shall be high
2. Condensation pressure shall be moderate
3. High thermal conductivity
4. Low viscosity in a liquid and gas phase
5. For safety reason, refrigerants shall be easily detected, if there is a leak
6. Easily obtained
7. Environmentally friendly

This research will examine n-pentane (C_5H_{12}) as the refrigerant for the ORC system. The n-pentane isomerization reaction of the porous solid acid catalyst was investigated at 198.0 °C, which is slightly higher than the critical temperature of n-pentane (Hou et al., 2003). The reactant pressure in the reactor is controlled so that the reaction liquid is in a gas, near critical, and supercritical state. The results show that the n-pentane conversion increases sharply with increasing pressure near the critical point. The amount of coking deposition depends very much on the pressure of the reaction fluid. The main reason for deactivation of the catalyst is precipitation coke on the catalyst. Deactivation of catalysts is suppressed at higher pressures because more coke precursors are produced in the reaction dissolved into liquid, which increases the stability of the catalyst. UV-vis, IR, thermogravimetric analysis and 1H NMR studies show that there are at least two types of catalyst surface coke precursors. The effect of pressure on coke properties is not large enough, even though it significantly affects the amount of coke deposition on the catalyst.

3 Research Method

Method used in this research is a literature and case study. Articles, journals and books which are discussing ORC, turbine and exergy which related with this research were used.

The case study was observed from primary and secondary data. The primary data for this research was collected from interview with key persons (i.e. Engineering Manager, Field Engineer, and Operator) of the ORC power plant. Furthermore, the secondary data was collected from the ORC performance from 100 sample.

Table 1 Performance data of the ORC system

P_0 MPa	P_1 MPa	P_2 Mpa	T_0 oC	T oC	T oC	$\dot{W}_{gen}$ kW	$\dot{m}$ kg/s
0,092	0,949	0,158	30	128	84	269	6,811

Table 1 shows secondary data from the ORC performance. The table shows the ambient temperature, heat source inlet temperature, heat source outlet temperature, and so forth. By utilizing Coolprop application, one can be obtained is enthalpy and entropy value as it is presented in table

4 Result and Discussion

4.1 Heat Relieved ($\dot{Q}_{out}$)

The value of heat relieved can be calculated as follow:

$\dot{Q}_{out}=\dot{m}(h1-h_2)-\dot{W}_{turbine}$
$= 6{,}811\ (506{,}903-444{,}535)-\dot{W}_{turbine}$

While $\dot{W}$turbine can be calculated as follow:

$= 6{,}811\ (506{,}903 - 444{,}535) - 273{,}98$
$= 150{,}869$ kW

4.2 Exergy Efficiency and Exergy Losses

To reveal the exergy efficiency, one need to be considered is the turbine reversible duty output ($\dot{W}_{rev,out}$) using the following equation:

$\dot{W}_{rev,out} = \dot{m}\ [(h_1-h_2)-T_0(s_1-s_2)]$
$= 6{,}811[(506{,}903-444{,}535)-30(1{,}348-1{,}368)]$
$= 428{,}847$ kW

Furthermore, the efficiency exergy and exergy losses can be calculated by using the following equation:

Exergy Efficiency

$\eta_{ex(turbine)} =(\dot{W}_{out}/(\dot{W}_{rev,out})) \times 100\%$
$= (294{,}89/463{,}32932) \times 100\%$
$= 63{,}88\ \%$

Exergy Losses

Exergy losses can be revealed as follow:
$ED = \dot{W}_{rev,out} - \dot{W}_{out}$
$= 428{,}847 – 273{,}998$
$= 154{,}86$ kW

Exergy Maximum Duty Potential

$\Psi = (h_1-h_0) – T_0(s_1-s_0)$
$= (506{,}903 - (-4{,}7445)) - 30(1{,}348-(-0{,}015))$
$= 471{,}278$ kJ/kg

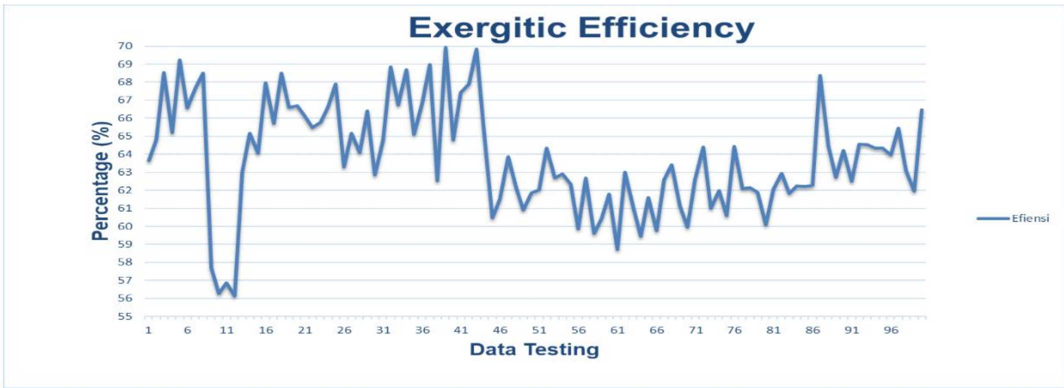

Figure 1 Turbine efficiency data from 100 sample

In general, the higher the ambient temperature and the input temperature in the turbine, will increase the efficiency as shown in Figure 1. It is supported by the finding in this research. The lowest efficiency of 56.24% occurred at the inlet temperature of 117oC and relatively low ambient temperature of 22oC. Meanwhile, the highest efficiency of 69.92% occurred at a relatively high inlet temperature of 133oC and ambient temperature of 33oC.

Figure 2 shows the exergy losses on the ORC system. Above's data can be viewed as imperfections in a system. A system is believed to continuously have losses while it is on duty.

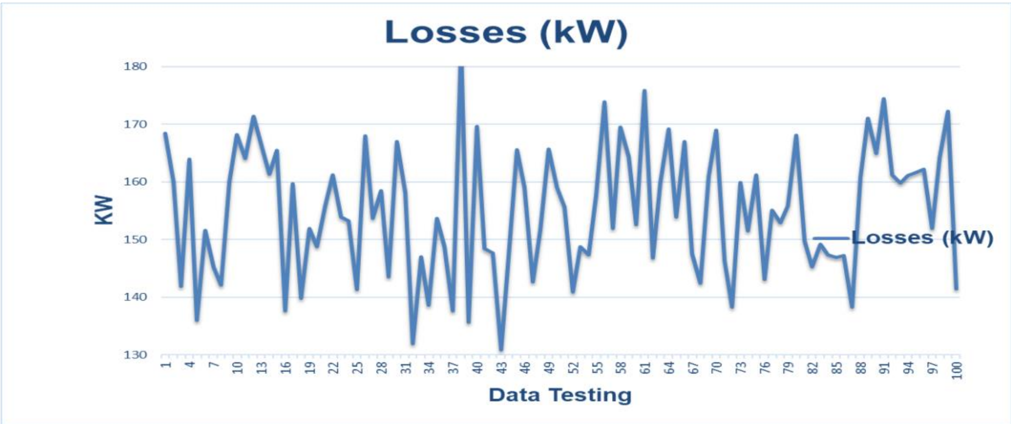

Figure 2 Exergy losses from 100 sample

5 Conclusion

Exergy Efficiency in the 500 kW ORC turbines is relatively small, fluctuated and tends to decrease, as it is shown in the first month of data collection in April 2018. During the early of week of April 2018, the temperature in the inlet heat source is 124^{o}C. Such condition made the generator producing a high power of 289 kW.

Meanwhile, in the late of April 2018 the inlet temperature in the heat source decreased to 117oC. Such condition made the generator power down to 215 kW. In the following months, the power output of the ORC system tends to be decreased.

The average power output of the turbine itself is 273,98 kW while the reversible duty is 428,84 kW. The turbine efficiency is recorded at 63,88%. The exergy losses of this ORC is 154,86 kW.

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